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Final Technical Report

Spin-Based Photonics via Electromagnetically Induced Transparency

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Award Number: N00014-03-1-0827

Summary

Research efforts have focused on the development and implementation of electromagnetically-induced transparency (EIT) from electron spin coherence in a semiconductor quantum well waveguide. Experimental studies have shown an induced transmission resonance arising from the electron spin coherence in the differential transmission spectrum. The induced resonance can be viewed as a signature of EIT from the electron spin coherence. Studies of the polarization and magnetic field dependence further confirm the physical mechanism of the induced resonance. The experimental results are in good agreement with the theoretical calculation. In addition, extensive experimental efforts have also been carried out to understand how electron spin coherence contributes to coherent nonlinear optical processes in semiconductors with the aim of further optimizing the EIT process.

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Objective:

- 1) Using electron spin coherence to realize electromagnetically induced transparency (EIT) in semiconductors.
- 2) Using EIT for applications such as tunable optical delays.

Note: While the grant is for three years, the funding ended after the first year due to the termination of the DARPA-SPINS program.

Approach:

- 1) Using light hole transitions in a quantum well wave guide to induce spin coherence and realize EIT.
- 2) Using slow light effects associated with the EIT to realize a tunable optical delay line.

Summary of important accomplishment:

- 1) We have proposed and carried out a detailed theoretical analysis of a novel scheme to induce electron spin coherence and to realize EIT in a GaAs quantum well waveguide. In this scheme, two electron spin states in the conduction band are coupled to a common light-hole valance band state via two dipole optical transitions, forming a V-type three-level system. A special feature of scheme is that electron spin coherence can be induced and EIT can be realized without the use of an external magnetic field.
- 2) We have carried out experimental implementation of EIT from electron spin coherence in the GaAs quantum well waveguide. We have designed and fabricated the waveguide structure. We have also designed and fabricated a miniature waveguide coupler attached to a cold finger in an optical cryostat. The home-made waveguide coupler enabled us to couple laser beams into and out of the QW waveguide held in the cryostat.

Our experimental studies have shown a clear signature of EIT from the electron spin coherence in the differential transmission (DT) spectrum. The degree of the transparency is currently limited to 10% due to the CW pump laser we have used. To demonstrate conclusively that the induced resonance in the DT spectrum arises from the electron spin coherence, we have carried out additional experimental studies that applied an external magnetic field to the QW sample. The direction of the external magnetic field is along the growth axis of the quantum well such that the presence of the external field does not affect the symmetry properties of the electronic transitions involved in the experiment. In this configuration, the spin coherence induced resonance in the DT spectrum appeared at a spectral position, which is one Zeeman splitting away from the zero pump-probe detuning, in agreement with the theoretical calculation.

3) To understand coherent optical processes associated with the electron spin coherence and especially to optimize the EIT process, we have carried out experimental studies based on the technique of quantum beats. We show that simple atomic-like descriptions of optical interactions involving the electron spin coherence fail completely in semiconductors. For mobile excitons, which are characteristic of extended optical excitations, quantum beats from the spin coherence vanish in the third order nonlinear optical response. The quantum beats, however, emerge in a fifth order nonlinear optical process with a highly unusual intensity dependence. These results, along with a theoretical analysis based on the N -exciton eigenstate model, reveal that in an excitonic system, the manifestation of electron spin coherence in coherent optical response depends critically on the underlying Coulomb interactions between the two excitons involved in the electron spin coherence. These studies have significantly improved our understanding of coherent nonlinear optics of electron spins in semiconductors.

4) We have carried out detailed experimental studies on fundamental decoherence processes in self-assembled CdSe quantum dots. The primary purpose of these studies is to understand intrinsic decoherence processes in self-assembled quantum dots and to lay the ground work for the use of these quantum dots in later EIT studies.

The experimental studies, which are based on the use of high-resolution spectral hole burning, have shown that the homogeneous linewidth in CdSe quantum dots is nearly the same as that in self-assembled InAs quantum dots. This is somewhat surprising since electron-phonon interactions in II-VI semiconductors such as CdSe are much stronger than those in III-V semiconductors such as GaAs or InAs. Our experimental results have provided valuable information for formulating a theoretical description of intrinsic decoherence processes in semiconductors.

Publications:

Tao Li, Hailin Wang, N.H. Kwong, and R. Binder, "*Electromagnetically induced transparency from electron spin coherence in a quantum well waveguide*," Opt. Express **11**, 3298 (2003).

Phedon Palinginis and Hailin Wang, "Vanishing and emerging of absorption quantum beats from electron spin coherence in GaAs quantum wells," Phys. Rev. Lett. **92**, 037402 (2004).

Phedon Palinginis, Hailin Wang, Serguei Gupalov, D.S. Citrin, M. Dobrowolska, and J. Furdyna, "Exciton dephasing in self-assembled CdSe quantum dots," Phys. Rev. B. **70**, 073302 (2004).

Phedon Palinginis and Hailin Wang, "Coherent Raman resonance from electron spin coherence in GaAs quantum wells," Phys. Rev. B **70**, 153307 (2004).

Susanta Sarkar, Phedon Palinginis, Hailin Wang, N.H. Kwong, and R. Binder, "Inducing electron spin coherence without magnetic field in semiconductor quantum well waveguides," Phys. Rev. B **72**, 035343 (2005).

Invited presentations:

Hailin Wang, "EIT from spin coherences in semiconductors," (plenary talk), Physics of Quantum Electronics, Plenary Talk (Snowbird, UT, 2004).

Hailin Wang, "EIT via exciton correlations," (invited paper), Photonics West (San Jose, CA, 2004).

Hailin Wang, "EIT from spin coherences in semiconductors," (invited paper), DARPA Advanced Technology Symposium (New Orleans, 2004).

Hailin Wang, "EIT from spin coherences in semiconductors," (invited paper), Cooperative Phenomena in Optics and Transport in Nanostructures (Dresden, Germany, 2004).

Hailin Wang, "EIT from spin coherences in semiconductors," (invited paper), Workshop on semiconductor quantum optics (Sellin, Germany, 2004).

Hailin Wang, "EIT in semiconductors," (invited paper), The 4th International Conference on Light-Matter Coupling in Nanostructures (St. Petersburg, Russia, 2004).

Hailin Wang, "EIT in semiconductors," (invited paper), Fundamental Optical Processes in Semiconductors (Estes Park, CO, 2004).

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Phedon Palinginis graduated with a PhD in Physics in 2004 and Susanta Sarkar graduated with a PhD in Physics in 2006.

Report of inventions

No patents were filed.